E76-10122
CR-146055

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APPLICATION OF LANDSAT TO THE SURVEILLANCE AND CONTROL OF LAKE EUTROPHICATION IN THE GREAT LAKES BASIN

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(E76-10122) APPLICATION OF LANDSAT TO THE SURVEILLANCE AND CONTROL OF LAKE EUTROPHICATION IN THE GREAT LAKES BASIN Progress Report, Nov. 1975 - Jan. 1976 (Bendix Corp.) 25 p HC $3.50 CSCL 08H G3/43 N76-16545 Unclas 00122

January 6
Type II Report for the Period of November 11 through January 11, 1976

Prepared for:

GODDARD SPACE FLIGHT CENTER

Greenbelt, Maryland 20771

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TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Application of LANDSAT to the Surveillance and Control of Lake Eutrophication in the Great Lakes Basin		5. Report Date January 1976
		6. Performing Organization Code
7. Author(s) Robert H. Rogers		8. Performing Organization Report No. BSR 4213
9. Performing Organization Name and Address Bendix Aerospace Systems Division 3621 South State Rd. Ann Arbor, Michigan 48107		10. Work Unit No.
		11. Contract or Grant No. NAS 5-20942
12. Sponsoring Agency Name and Address Goddard Space Flight Center Greenbelt, Md. 20771		13. Type of Report and Period Covered Type II - November 1975-January 1976
		14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

This paper reports on the results achieved during the fourth three month period to establish cost benefits of LANDSAT for the surveillance and control of Lake eutrophication. This goal is being accomplished by producing LANDSAT products for an EPA modeling study of Saginaw Bay and inland lake surveys by the Michigan and Wisconsin DNR's. These user agencies are, in-turn, providing detailed ground truth on water quality and are participating in studies and evaluations to determine the cost benefits of LANDSAT.

17. Key Words (Selected by Author(s))	18. Distribution Statement		
Water quality, land-use, computer processing, lake eutrophication, ERTS, and LANDSAT			
19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*

PREFACE

Program Objectives

The overall objective of this investigation is to establish the cost benefits of using LANDSAT on an operational basis in the surveillance and control of lake eutrophication. This objective is accomplished by supporting, with LANDSAT data products, bona fide users who will evaluate the data's usefulness to on-going programs concerned with the classification and control of lake eutrophication. The products supplied to the users will be made as applicable as possible to their data needs. The following therefore, are specific objectives to be addressed:

1. To identify the data requirements of the users and to relate these to LANDSAT data with respect to land-water categories, detail, scale, and frequency.

2. To identify water quality parameters which relate directly to eutrophication and to determine quantitative levels of these parameters by which lakes may be categorized as to trophic state.

3. To identify land-use patterns which relate to trophic state.

4. To develop and apply LANDSAT data imaging and interpretation techniques to categorize water and land-use features identified in order to produce information products of value to users.

Scope of Work

This investigation is supplying LANDSAT-derived information products to three federal and state agencies which are involved in the planning and management of lakes and watershed land use in the Great Lakes basin. Support is provided to the Environmental Protection Agency water quality survey and modeling study of lake eutrophication in Saginaw Bay; the State of Michigan Department of Natural Resources Survey of inland lakes and watersheds for the purpose of assessing the degree of eutrophocation in these lakes and the potential for further enrichment and pollution due to land-use practices; and the State of Wisconsin Department of Natural Resources lake survey to determine eutrophication status, causes, effects, and control treatments.

For each of these three programs, this investigation is analyzing and interpreting LANDSAT data to provide the three user agencies with land-use and lake water quality information about their specific test areas. The usefulness of LANDSAT data to each type of study and the cost benefits of its use over alternative data collection systems is being evaluated.

Conclusions

Chemical and biological water quality data collected July 31, 1975 at 16 stations within Saginaw Bay, Michigan, in concert with a LANDSAT overflight, have been processed to enable prediction of water quality in non-sampled areas. Measurements included; temperature, secchi depth, conductivity, chloride, chlorophyll $\bar{a}$, total kjeldahl nitrogen and total phosphorous. When these were treated as dependent variables and LANDSAT measurements as independent variables, and processed with a stepwise linear regression analysis, all but one parameter had correlation coefficients greater than that for the 99% level of significance. Chloride, conductivity, total kjeldahl nitrogen, total phosphorus and chlorophyll $\bar{a}$ were best correlated with the ratio of LANDSAT Band 4 to Band 5. Temperature and Secchi depth were best correlated to Band 5. Results of the regression were used to map the water quality parameters over the entire bay.

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1. REVIEW OF PROGRAM AND RESULTS

This section reports on the work accomplished and results achieved during the fourth three month period of a program to establish the cost benefits of LANDSAT for the surveillance and control of lake eutrophication. To accomplish this goal, LANDSAT data products are being generated to support the Environmental Protection Agency (EPA) modeling study of lake eutrophication in Saginaw Bay; the State of Michigan's survey of inland lakes and watersheds for the purpose of assessing the effects of watershed land use on lake water quality; and the State of Wisconsin's lake survey to determine eutrophication status, causes, effects, and control treatments.

These user agencies are providing, at no cost to NASA, user needs which include desired data formats, data timeline requirements (i.e., how fast data are needed and how long it maintains its value before update is needed), and data accuracy requirements (i.e., geometric and classification accuracy). These agencies are also providing detailed ground truth on water quality and watershed land use in conjunction with LANDSAT overflights and are participating in studies and evaluations to determine the usefulness and cost benefits of the LANDSAT data products.

The remainder of this section is subdivided to report on the work accomplishments and results achieved to support the on-going water quality programs of the three user agencies.

1.1 SUPPORT FOR THE EPA STUDY OF WATER QUALITY IN SAGINAW BAY

Coordination meetings were held with the EPA in order to review LANDSAT data requirements and to develop plans to provide the needed aircraft and LANDSAT support.

The EPA is sponsoring a 36-month study of water quality in Saginaw Bay, which will terminate in June 1976. Important goals of this study are to describe, on a seasonal basis, the circulation and water masses in Saginaw Bay; to monitor inputs of nutrients from its watershed; and to develop and evaluate models for predicting water quality in the bay as a function of various control strategies.

To achieve these goals, the EPA is using LANDSAT data products produced by this investigation and surface/subsurface measurements obtained by the Cranbrook Institute of Science, under the direction of Dr. V. Elliott Smith (LANDSAT Co-Investigator). The surface measurement program has been underway since April of 1974. From each of 61 stations distributed over Saginaw Bay, some 30 water quality parameters are derived on an 18-day cycle that coincides with the LANDSAT overflights. On 1 April 1975, this measurement program was shifted from the LANDSAT-1 to the LANDSAT-2 schedule.

The first clear LANDSAT scene of the bay, coincident with surface measurements at the bay stations, was a 3 June 1974 scene. Techniques used in the computer processing of this scene were reported in the first Type II report. The results achieved in processing this scene cover two phases of the investigation. Phase I was reported on in the first Type II report and Phase II in the third Type II report.

<u>Phase I</u> - Of particular importance was the demonstration of a technique for editing LANDSAT measurements using the latitudes and longitudes of bay stations having known (measured) water quality parameters. At the time of the initial processing effort, the only parameter fully reduced for all bay stations which is a good indicator of turbidity was Secchi depth. Consequently this initial processing effort resulted in a geometrically-corrected color-coded image of Saginaw Bay showing nine discrete colors (categories) of turbidity, as indicated by nine Secchi depths between 0.3 and 3.3 meters.

<u>Phase II</u> - To determine further relationships between LANDSAT measurements and water quality parameters the 3 June 1974 measurements from 27 bay stations of known chemical and biological parameters were edited and processed by a stepwise linear regression program. The water quality parameters included; temperature, secchi depth, conductivity, chloride, chlorophyll $\bar{a}$, sodium, potassium, magnesium, calcium, total dissolved phosphorous, total kjeldahl nitrogen and total phosphorous. When these parameters were treated as dependent variables and LANDSAT measurements as independent variables all but one water quality parameter had correlation coefficients greater than that for the 95% level of significance. The regression correlation coefficients varied from 0.99 for total phosphorus to 0.72 for chlorophyll $\bar{a}$ corrected. Five of the water quality parameters were best correlated with LANDSAT Band 6 alone. One parameter, temperature, related to Band 5 alone and only two bands were justified for mapping the remaining six parameters.

This report concerns the use of similar computer processing techniques, however the first application of the regression technique (Phase II) only evaluated the four LANDSAT bands as the independent variables and concluded that Band 6 alone was sufficient and the most important band for predicting values of most of the water quality parameters. This investigation has extended this analysis by using the ten independent variables; the LANDSAT bands individually (Bands 4, 5, 6, and 7); and the six non-redundant ratios (Bands 4/5, 4/6, 4/7, 5/6, 5/7, and 6/7) in the regression program to process the 3 June 1974 scene and a 31 July 1975 scene (2190-15404). This analysis shows that a ratio of bands is more strongly correlated to most water quality parameters. The correlation of these parameters with one another indicates that the transport of Saginaw River water can now be traced by a number of water quality parameters, one or more of which are directly detected by LANDSAT. Chloride, conductivity, total Kjeldahl nitrogen, total phosphorus, and chlorophyll $\bar{a}$ are best correlated with the ratio of LANDSAT Band 4 to Band 5. Temperature and Secchi depth correlate best with Band 5.

1.2 SUPPORT FOR MICHIGAN'S SURVEY OF INLAND LAKES AND WATERSHEDS

To review the State of Michigan program, the Michigan Department of Natural Resources (DNR) is committed, under the State Federal Water Pollution Control Act (Act 92-5000), to a state-wide survey of public lakes and their watersheds for the purpose of assessing the degree of eutrophication in these lakes and the potential for further enrichment and pollution resulting from land-use development in the watershed. A requirement of the DNR program, as well as programs of other governmental agencies concerned with the maintenance and control of water quality, is to develop a knowledge of the interrelationships between the water quality parameters (turbidities, chlorophyll concentrations, etc.) and watershed land-use parameters (categories and coverage).

To obtain the needed information, the Michigan DNR has selected 19 test lakes whose watersheds contain various levels of urbanization. LANDSAT data acquired on July 30, 31, and August 1, 1975 will be used to inventory land cover within these watersheds. The land cover mapped by LANDSAT will be correlated with lake water quality measurements obtained by the DNR and the University of Michigan Biological Station. LANDSAT capability to map water quality parameters directly as done for Saginaw Bay will also be investigated.

The third Type II report reviewed two recently completed investigations which demonstrated LANDSATs capability to inventory watershed land-use and the techniques that will be used for the Michigan inventory.

Topographic maps, 7 1/2 or 15 min, for each of the 19 lake watersheds have been received. In the interim between receipt of NASA photographic coverage (now rescheduled), aerial photography has been obtained for some of the lakes and has been ordered, for the remaining lakes, from the Agricultural Stabilization and Conservation Service (USDA).

Computer processing of the LANDSAT CCTs for the test area lakes is due to begin January 19, 1976.

1.3 SUPPORT FOR WISCONSIN'S SURVEY OF INLAND LAKES

As noted earlier, the Wisconsin DNR is also attempting to develop a method of lake classification by trophic level, as required by Section 314 of Federal Water Pollution Control Amendments (1972). Accordingly, the Wisconsin DNR is evaluating the utility of LANDSAT data products directed towards this goal.

The second Type II report described the techniques used by this investigation to categorize several hundred lakes in the Madison and Spooner, Wisconsin area. More recently it has been determined that the following categories of trophic state of the lakes can be identified through computer processing of LANDSAT data: algae lakes (of various degrees), deep clear water lakes, clear water lakes with weeds, silt and sand bottom lakes, and tannin water. It has not been possible to separate tannin water from tannin water with mud, nor tannin water from tannin water with ice. The results of recent categorization efforts must be field checked before the overall results can be evaluated. Categorization of both Spring and Fall LANDSAT imagery is being considered to help separate bottom type from water type.

2. SIGNIFICANT RESULTS

Computer techniques have been developed for mapping water quality parameters from LANDSAT data, using surface samples collected in an ongoing survey of water quality in Saginaw Bay (Lake Huron), Michigan, sponsored by the US Environmental Protection Agency. Chemical and biological parameters were measured on 31 July 1975 at 16 bay stations in concert with the LANDSAT overflight. Application of stepwise linear regression to seven of these parameters and corresponding LANDSAT measurements resulted in regression correlation coefficients that varied from 0.94 for temperature to 0.71 for Secchi depth. Chloride, conductivity, total Kjeldahl nitrogen, total phosphorus, and chlorophyll a were best correlated with the ratio of LANDSAT Band 4 to Band 5. Temperature and Secchi depth were best correlated to Band 5. Results of the regression analysis were used to map the water quality parameters over the entire bay.

3. PROBLEMS

No problems are impeding this investigation.

4. RECOMMENDATIONS

None

5. PUBLICATIONS

No official publications, but through February 1976, three reports (papers) have been published as contributions to three technical symposiums.

6. FUNDS EXPENDED

Total expenditures through 11 January 1976 are $56,730.

7. DATA USE

A tabulation showing the total value of the data allowed and received through 31 December 1975 follows:

Value of Data Allowed	Value of Data Ordered	Value of Data Received
$5,550	$3,243	$2,843

8. AIRCRAFT DATA

By prior arrangement with NASA Johnson Space Center in Houston, supportive M^2S and photographic coverage of the test areas in Michigan (August 18, 1975, Flight No. 2, Mission 317) will be reflown between July 1 - September 1, 1976 and time-phased with LANDSAT 2 overpass.

APPENDIX A

TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Computer Mapping of Water Quality in Saginaw Bay with LANDSAT Digital Data		5. Report Date January 1976 6. Performing Organization Code
7. Author(s) V. E. Smith, R. H. Rogers, N. J. Shah, J. B. McKeon		8. Performing Organization Report No. BSR 4213
9. Performing Organization Name and Address Bendix Aerospace Systems Division 3621 South State Road Ann Arbor, Michigan 48107		10. Work Unit No. 11. Contract or Grant No. NAS 5-20942 13. Type of Report and Period Covered
12. Sponsoring Agency Name and Address Goddard Space Flight Center Greenbelt, Maryland 20771		Special Report 14. Sponsoring Agency Code

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16. Abstract

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17. Key Words (Selected by Author(s))	18. Distribution Statement
LANDSAT, Computer Processing Regression Analysis, Water Quality, Ratio Imagery	

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified		13	

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COMPUTER MAPPING OF WATER QUALITY IN SAGINAW BAY WITH LANDSAT DIGITAL DATA

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BIOGRAPHICAL SKETCHES

Dr. Robert H. Rogers is a senior engineer at Bendix, where he is a Supervisor in the Earth Resources Interpretations Group. Rogers received his BS from Tri-State College, his MS from Southern Methodist University, and his PhD in EE from Michigan State University. He is a member of the ASP, and has published more than 30 papers on the applications of remote sensing data. Dr. John B. McKeon and Dr. Navinchandra J. Shah are Project Investigators in the Interpretations Group and are involved in the computer processing and analysis of LANDSAT, Skylab, and Bendix Multispectral Scanner data. Dr. McKeon, a telegeologist and member of ASP, received a BA in Natural Sciences from John Hopkins University, an MS in Geology from the University of Maine, and his PhD from Ohio State University. Dr. Shah received his BS from the University of Madras in India and his MS and PhD in Physics from the University of Michigan. He has published numerous papers on the applications of remote sensing. Dr. V. Elliott Smith is Coordinator of Lake Research at Cranbrook Institute of Science, where he is the Principal Investigator for an EPA-funded survey of water chemistry in Saginaw Bay (Lake Huron). Smith received his BS and MS degrees in Biology from Florida State University and his PhD in Marine Biology from Scripps Institution of Oceanography. He has published several papers in the fields of biochemistry, biology, and remote sensing.

ABSTRACT

Computer techniques have been developed for mapping water quality parameters from LANDSAT data, using surface samples collected in an ongoing survey of water quality in Saginaw Bay (Lake Huron), Michigan, sponsored by the US Environmental Protection Agency. Chemical and biological parameters were measured on 31 July 1975 at 16 bay stations in concert with the LANDSAT overflight. Application of stepwise linear regression to seven of these parameters and corresponding LANDSAT measurements resulted in regression correlation coefficients that varied from 0.94 for temperature to 0.71 for Secchi depth. Chloride, conductivity, total Kjeldahl nitrogen, total phosphorus,

and chlorophyll $\bar{a}$ were best correlated with the ratio of LANDSAT Band 4 to Band 5. Temperature and Secchi depth were best correlated to Band 5. Results of the regression analysis were used to map the water quality parameters over the entire bay.

INTRODUCTION

In response to environmental requirements for large-area surveillance of water quality and watershed land use, NASA's LANDSAT-2 investigation is establishing the cost benefits of LANDSAT to the surveillance and control of lake eutrophication in the Great Lakes Basin. To accomplish this objective, LANDSAT data products are being generated to support the United States Environmental Protection Agency (EPA) modeling study of eutrophication in Saginaw Bay; the State of Michigan's survey of inland lakes and watersheds for the purpose of assessing the effects of watershed land use on lake water quality; and the State of Wisconsin's lake survey to determine eutrophication status, causes, effects, and control treatments. One goal of this work is to determine which water quality parameters best correlate with LANDSAT measurements. This paper reports on results directed toward this goal using water quality parameters and LANDSAT data acquired on 31 July 1975 in the Saginaw Bay test area.

Several institutions and federal agencies in the United States and Canada are conducting a comprehensive survey of water quality and circulation in Lakes Huron and Superior (the Upper Lakes Reference Study, a part of the United States/Canadian Great Lakes Water Quality Agreement of 1972). In Saginaw Bay (Lake Huron), EPA is sponsoring a 36-month modeling study of water quality. EPA's program will develop a deterministic model that will describe water quality changes within the bay and their relationships to enrichment and pollution caused by man. The resulting model will be used to evaluate various strategies to control nutrient flow into the bay. Important goals in this project are to describe, on a seasonal basis, the circulation and water quality in Saginaw Bay, to monitor inputs of nutrients from its watershed, and, ultimately, to develop and evaluate models for predicting water quality in the bay as a function of various control strategies.

A number of investigators have reported on the feasibility of determining various water quality parameters from LANDSAT data. Klemas (Ref 1)* has used Secchi depth and suspended sediment measurements as correlated with Band 5 image radiance to map turbidity and circulation patterns in Delaware Bay. Yarger (Ref 2) has processed multidate digital data for reservoirs in Kansas to study the effects of sun angle change, and has studied the 5/4, 6/4, and 7/4 band ratios to predict suspended solids (ppm) at unsampled areas from ground truth samples. Johnson (Ref 3) has applied the equations for predicting suspended sediment derived from stepwise regression analysis of ground truth data from Delaware Bay to image data for Chesapeake Bay and has found reasonable agreement with ground truth measurements for Chesapeake Bay.

*References are located at the end of this paper.

This LANDSAT-2 investigation has produced two previous reports (Refs 4 and 5). The first discusses the applications of a supervised computer processing technique to a 3 June 1974 LANDSAT scene (1680-15455) to produce a geometrically-corrected color-coded image of Saginaw Bay which shows nine discrete categories of turbidity, as indicated by nine Secchi depths between 0.3 and 3.3 meters. This first effort was limited to the consideration of the Secchi depth parameter as an indicator of turbidity and the application of the supervised processing technique to correlate the Secchi depth parameter to the LANDSAT measurements. More recently (Ref 5), this investigation reprocessed the same June 1974 scene to develop relationships between 12 of the water quality parameters and the LANDSAT measurements by a stepwise linear regression program (Ref 6). This first application of the regression technique only evaluated the four LANDSAT bands as the independent variables and concluded that Band 6 alone was sufficient and the most important band for predicting values of most of the water quality parameters. This paper extends this analysis by using the ten independent variables; the LANDSAT bands individually (Bands 4, 5, 6, and 7); and the six non-redundant ratios (Bands 4/5, 4/6, 4/7, 5/6, 5/7, and 6/7) in the regression program to process the 3 June 1974 scene and a 31 July 1975 scene (2190-15404). This analysis shows that a ratio of bands is more strongly correlated to most water quality parameters.

Mapping specific ranges of a water quality parameter by a supervised technique requires subdividing the parameter of interest into discrete categories, locating and editing LANDSAT measurements corresponding to each category, and applying the training measurements to categorize other LANDSAT picture elements ("pixels"). This technique is well established and is by far the most efficient procedure for mapping land-cover categories, i.e., urban, grassland, bare soil, water, etc., in which the spectral characteristics of the categories are very different (uncorrelated). The application of this same processing technique to mapping the amount or concentration of a continuous water quality parameter, i.e., Secchi depth, chlorophyll concentration, etc., may not be justified as better estimates of the parameter may be obtained with less effort by a simpler technique. If a continuous equation can be established between the parameter and LANDSAT, e.g., the equation of a straight line with one independent and one dependent variable, its solution would provide many more estimates of the desired parameter than would be practical by the supervised technique, which requires a training set for each discrete value of the parameter. This paper investigates this possibility by applying a stepwise linear regression program to seven water quality parameters and LANDSAT measurements observed on 31 July 1975 at 16 stations in Saginaw Bay (Table 1).

TEST AREA

Saginaw Bay is a shallow extension of Lake Huron and is bounded by five counties of southeastern Michigan (Figure 1). The bay has an area of some 2,960 km^2 and a maximum length and width of 82 km and 42 km, respectively. The mean depths are 4.6 m for the inner bay and 14.6 m for the outer bay. The Saginaw River enters the bay at its extreme

Table 1. Water Quality and LANDSAT Data for Saginaw Bay on 31 July 1975. Measurements Were Made at Water Depths of One Meter

Station	Number of Pixels to Station Area	Temperature (°C)	Secchi Depth (m)	Chloride (mg/l)	Conductivity (micromhos)	Total Kjeldahl Nitrogen (mg/l)	Total Phosphorus (mg/l)	Chlorophyll $\bar{a}$ (µg/l)	Mean Reflectance of Station Area, Band 4 254*	5 254*	6 254*	7 252*	Ratio of Station Area Means, Band Ratio 4/5	4/6	4/7	5/6	5/7	6/7
7	56	26.1	1.9	10.9	243.	0.37	0.012	20.70	40.6	27.5	14.8	1.4	1.48	2.74	29.00	1.86	19.64	10.57
8	63	26.7	1.6	11.1	258.	0.41	0.017	9.38	44.0	29.5	16.3	1.5	1.49	2.70	29.33	1.81	19.67	10.87
12	72	26.8	1.3	18.8	277.	0.65	0.027	10.70	42.8	29.5	16.2	1.7	1.45	2.64	25.18	1.82	17.35	9.53
18	72	23.6	2.0	9.8	237.	0.38	0.012	5.61	38.1	24.7	13.8	0.5	1.54	2.76	76.20	1.79	49.40	27.60
26	64	26.0	1.6	13.8	251.	0.35	0.018	11.60	42.7	28.3	14.7	0.4	1.51	2.90	106.75	1.93	70.75	36.75
27	90	23.7	2.0	10.1	239.	0.29	0.012	7.38	38.1	24.5	12.2	0.3	1.56	3.12	127.00	2.01	81.67	40.67
32	100	24.8	1.8	10.1	235.	0.33	0.010	7.38	37.2	23.2	11.7	0.1	1.60	3.18	372.00	1.98	232.00	117.00
34	100	26.9	0.6	24.1	294.	1.00	0.039	68.50	38.6	29.1	16.4	0.9	1.33	2.35	42.89	1.77	32.33	18.22
38	121	25.1	1.4	11.7	244.	0.29	0.014	13.60	40.4	26.1	12.3	0.1	1.55	3.28	404.00	2.12	261.00	123.00
42	72	20.4	5.5	6.6	211.	0.14	0.002	1.84	32.3	20.3	9.8	0.3	1.59	3.30	107.67	2.07	67.67	32.67
43	72	23.5	1.5	12.1	246.	0.42	0.013	15.60	36.0	23.1	10.9	0.2	1.56	3.30	180.00	2.12	115.50	54.50
44	72	24.4	1.0	20.1	281.	0.72	0.027	37.10	35.6	25.5	14.5	0.8	1.40	2.46	44.50	1.76	31.88	18.13
52	72	21.5	2.1	10.4	238.	0.33	0.009	10.00	32.3	21.1	11.0	0.4	1.53	2.94	80.75	1.92	52.75	27.50
56	72	23.7	2.2	10.6	244.	0.26	0.014	6.58	39.5	25.2	12.8	0.6	1.57	3.09	65.83	1.97	42.00	21.33
60	110	22.5	5.0	6.9	215.	0.17	0.004	1.84	34.0	21.0	10.1	0.1	1.62	3.37	340.00	2.08	210.00	101.00
61	99	25.7	1.2	12.7	252.	0.42	0.020	18.00	43.7	28.7	14.1	0.6	1.52	3.10	72.83	2.04	47.83	23.50
Mean	81.7	24.46	2.0	12.5	247.8	0.41	0.016	15.36	38.5	25.4	13.2	0.6	1.52	2.95	131.50	1.94	84.47	42.05
Std. Dev.		1.92	1.3	4.7	21.8	0.22	0.009	16.53	3.8	3.1	2.2	0.5	0.08	0.32	126.54	0.13	79.12	37.66

*Maximum pixel count.

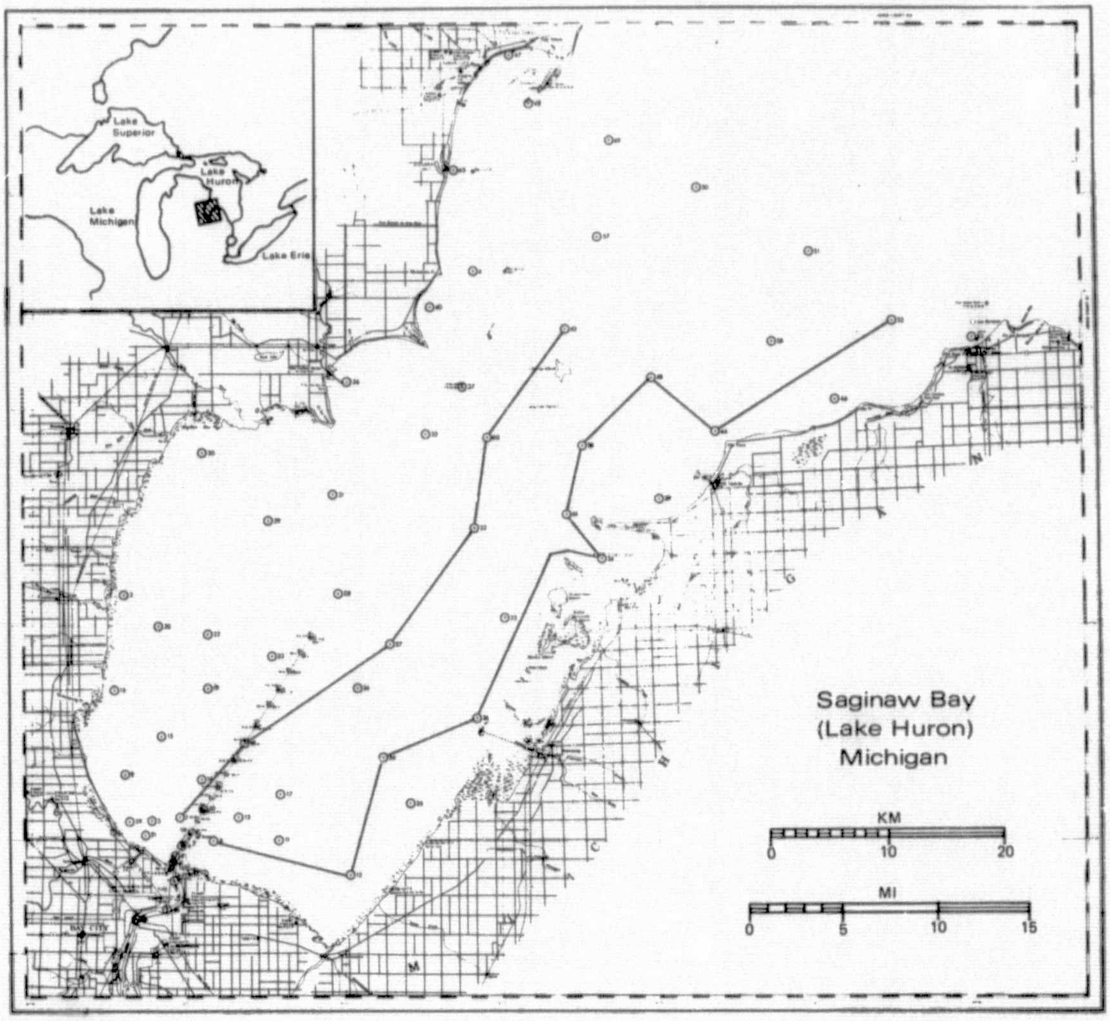


Figure 1. Map of Saginaw Bay, Showing the 61 Water Quality Stations by the Symbol ⊙. The Cruise Tracks of the Two Vessels and the 16 Stations Sampled on the Day of the LANDSAT Overpass (31 July 1975) are also Shown.

southwestern end and contributes approximately 90% of the pollutants found in the bay (Ref 7). This river and its tributaries drain a watershed of more than 16,060 km^2 and contain four major cities and much agricultural land. Consequently, inputs of salts, nutrients, and pollutants to the bay have been increasing for many years. Levels of turbidity and algal production are consistently high, especially within the inner bay. Major declines in commercial fish yields, wildfowl populations, and esthetic values have resulted from this eutrophication. The natural estuarine-like movement of pollutants from the bay into southern Lake Huron may also reduce water quality throughout the lower Great Lakes. While circulation within the bay is highly wind-dependent, the pattern is generally counterclockwise. Clear Lake Huron water enters mainly along the western shore; turbid bay water exists along the eastern shore. Significant but unknown quantities of sediment are re-suspended regularly by wave action. The lower two-thirds of Saginaw Bay usually freezes over during January and February. These and other characteristics of Saginaw Bay have been documented by Freedman (Ref 7).

WATER SAMPLE PROGRAM

The EPA measurement program in Saginaw Bay is creating a data bank of water quality information that is being used to develop and test models of circulation, nutrient loadings, and algal productivity. Since April of 1974, surface and subsurface measurements have been obtained at the 61 bay stations shown in Figure 1, at 18-day intervals coinciding with LANDSAT overflights. Normally, three consecutive days are required to sample all stations. For this study, only measurements from stations sampled the day of the LANDSAT overpass were processed. These 16 stations are shown in Figure 1 linked by solid lines indicating the tracks of the two sample boats. The sampling began about three hours before and ended about eight hours after the satellite overpass.

On-site measurements at each bay station include temperature, pH, dissolved oxygen, conductivity, alkalinity, and water clarity. Clarity is indicated by Secchi depth and percent transmittance measurements. Variables measured in the laboratory include soluble nutrients (nitrate-nitrite, orthophosphate, sulfate, silicate, and ammonia), organic materials (nitrogen, phosphorus, carbon, and chlorophylls), chloride and metals (sodium, potassium, calcium, magnesium, and six trace metals), and total suspended solids. Enumerations of phytoplankton and zooplankton are also made. Coordinated studies of current patterns, nutrient inputs, and bottom fauna are also underway by EPA.

COMPUTER PROCESSING OF LANDSAT DATA

The LANDSAT computer-compatible tapes (CCTs) for this investigation were processed on the Bendix Multispectral Data Analysis System (MDAS) (Ref 4). Four major processing steps were involved; (1) transforming the locations of the bay stations from navigation charts to LANDSAT CCT coordinates, (2) extracting the LANDSAT digital measurements from the CCTs for each of the 16 bay station areas, (3) applying stepwise regression to the water quality parameters and LANDSAT measurements derived from each bay station area, and (4) producing a ratio image of the regression results on the film recorder.

Earth-to-LANDSAT coordinate transformation

Three basic steps were involved in the automatic referencing of ground coordinates to LANDSAT coordinates. The first step consisted of automatically retrieving the latitude and longitude of carefully selected ground control points (GCPs) from a map through a digitizing process. The criteria for selecting these GCPs is that they can be easily and accurately identified on LANDSAT imagery. The second step consisted of converting the latitude and longitude of these GCPs to LANDSAT coordinates by using a theoretical transformation derived from known and assumed spacecraft parameters, including heading, scan rate, altitude, and a knowledge of earth rotation parameters. The LANDSAT coordinates and transformation matrices thus obtained are approximate, based on the use of the nominal spacecraft parameters. The approximately-derived LANDSAT coordinates and transformation are used, however,

to identify the actual LANDSAT coordinates associated with the GCPs. To accomplish this, the coordinates of a GCP are input to the Bendix MDAS. The approximate transformation computes the LANDSAT coordinates and displays the area on the TV monitor. Positional errors of the GCPs displayed to the operator are designated by a cursor to the computer, which uses the error measurement to derive an improved set of coefficients for the transformation matrix. This procedure is repeated on additional GCPs until the desired geometric accuracy is achieved. This investigation used 20 GCPs within the LANDSAT scene. The resulting bay station coordinates were transformed to LANDSAT coordinates with an error of less than one picture element (pixel). A LANDSAT pixel corresponds to an area of 57 by 79 m (0.44 hectares).

LANDSAT measurements from station areas

The MDAS TV monitor was used to display the single pixel best corresponding to each bay station location. A cursor was then positioned, expanded, and shaped by the operator about each station site to designate a station area of 60 to 100 pixels in size. Once the station areas were designated, the MDAS computer extracted the measurements from all pixels defined by the cursor and calculated the mean digital count in each band (Table 1). For the table shown, the digital counts from the standard LANDSAT CCT have been multiplied by two in Bands 4, 5, and 6 and by four in Band 7. The six non-redundant ratios of the four LANDSAT bands were calculated from the station area means. The mean values of the digital counts in each LANDSAT band and the ratios of the means for each bay station were then stored in a disk file for use in the regression analysis.

Stepwise regression analysis

The LANDSAT measurements stored on the disk file were used in a stepwise linear regression program (Ref 6) to investigate relationships between the LANDSAT measurements and each of seven water quality parameters. The stepwise regression procedure first determined which single independent variable (one of the four LANDSAT bands or the six ratios) provided the best statistical correlation with the dependent variable (one of the water quality parameters). In successive steps, a second independent variable was added, if necessary, to improve the multiple correlation.

Filming water quality parameters

MDAS was used to produce a color-coded image of the ratio of Band 4 to Band 5, which was determined by the regression procedure to be the single best variable for mapping five of the seven water quality parameters. The ratio image was viewed with 24 color levels on the MDAS TV display. These levels were grouped to seven final levels. The ratio image, produced on an Optronics film recorder, was used with the regression equations to interpret the various water quality parameters over the bay.

STATISTICAL RESULTS

The results of applying the regression program to the 31 July 1975 scene are summarized in Table 2. The results for only the first step of the regression are reported since, in every case, the correlation coefficient was not significantly improved by adding other independent variables. The constants, coefficients, and most significant band or ratio of bands listed in the table may be used to predict the dependent variable. For example:

Chloride (mg/l) = 99.27 - 57.138 (Band 4/Band 5)

The regression correlation coefficient noted in the table provides a measure of the fit of the regression equation to the data and has a maximum value of unity. The standard error of estimate has the same units as the dependent variable and is the statistical standard deviation. Approximately 68% of the measurements are expected to be within one standard deviation of the mean.

Table 2. Regression Results for Saginaw Bay on 31 July 1975 (16 Stations)

Dependent Variable (Units)	Equation Constant	Equation Coefficient	Independent Variable (LANDSAT Band or Band Ratio)	Regression Correlation Coefficient (r)	Standard Error of Estimate
Temperature (°C)	9.688	+ 0.5804	Band 5	0.944 **	0.6560
Secchi Depth (m)	9.707	- 0.3010	Band 5	0.711 *	0.9650
Chloride (mg/l)	99.27	- 57.138	Band 4 to Band 5	0.922 **	1.891
Conductivity (micromhos)	650.0	- 264.82	Band 4 to Band 5	0.920 **	8.876
Total Kjeldahl Nitrogen (mg/l)	4.455	- 2.664	Band 4 to Band 5	0.934 **	0.0799
Total Phosphorus (mg/l)	0.1846	- 0.1112	Band 4 to Band 5	0.914 **	0.0039
Chlorophyll $\bar{a}$ (ug/l)	303.1	- 189.4	Band 4 to Band 5	0.869 **	8.455

* Significant at $P < 0.01$ ($r = 0.606$)
** Significant at $P < 0.001$ ($r = 0.725$)

Figure 2 shows the correlation between one of the seven water quality parameters (dependent variable) and the LANDSAT Band 4 to Band 5 ratio (independent variable). The figure shows the 16 sample points, the regression line and equation, the standard estimate of error (dashed lines), and the regression correlation coefficient (Table 2).

Figure 3 provides a visual evaluation of the overall fit of the regression equation for one of the seven water quality parameters. The regression equation and the appropriate independent variable values (Band 4 to Band 5 ratios) shown in Table 1, were used to arrive at predicted values of each water quality parameter. These predicted values, were, in turn, plotted against the measured values. If the regression equation resulted in a perfect correlation, all points would fall on a straight line having unity slope. The standard error of estimate is shown in Figure 3 as the dashed lines.

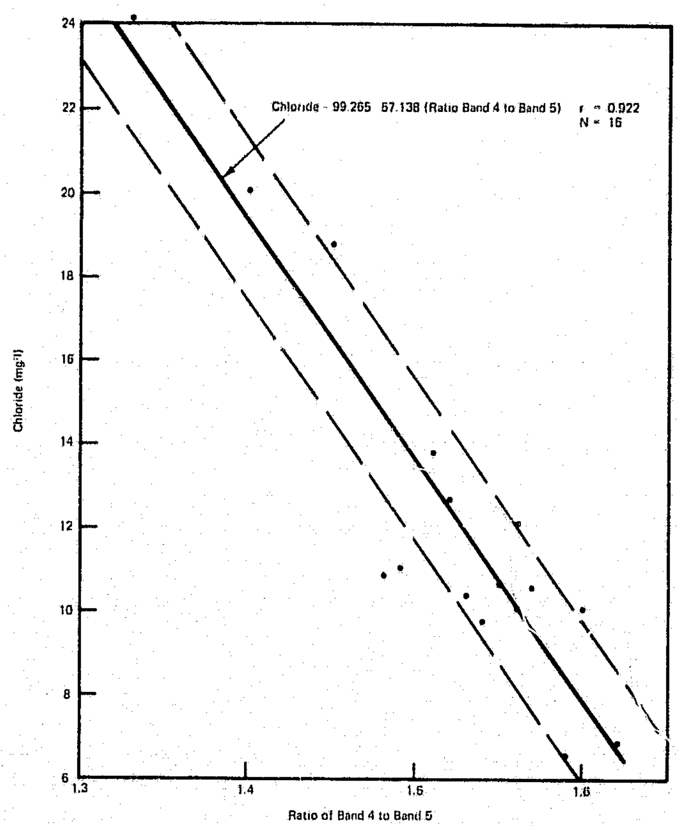


Figure 2. Chloride versus the Ratio of LANDSAT Band 4 to Band 5

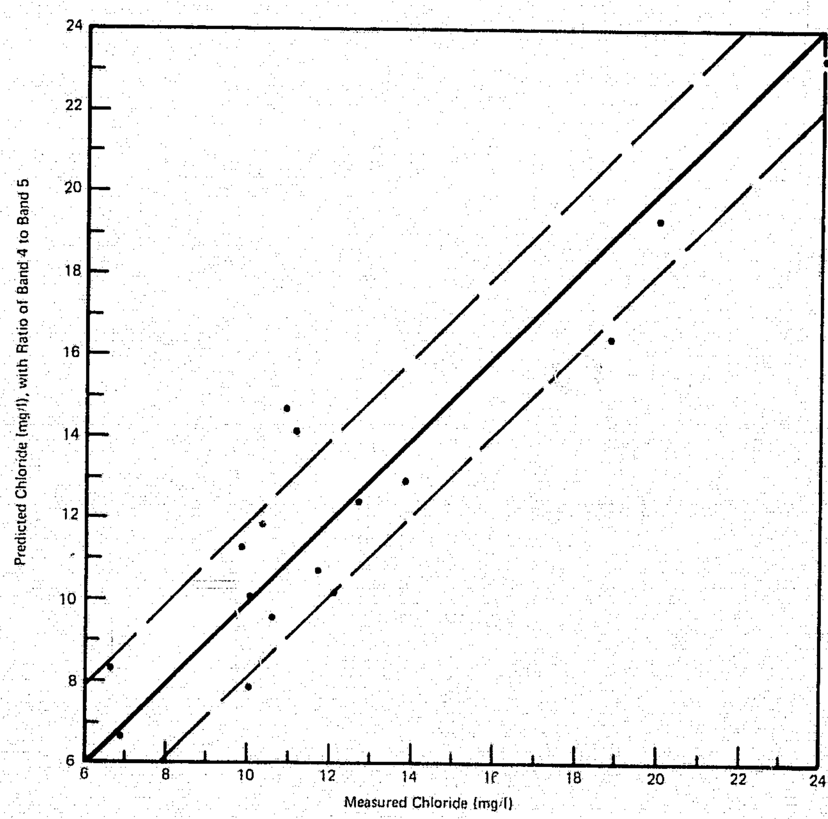


Figure 3. Predicted versus Measured Chloride

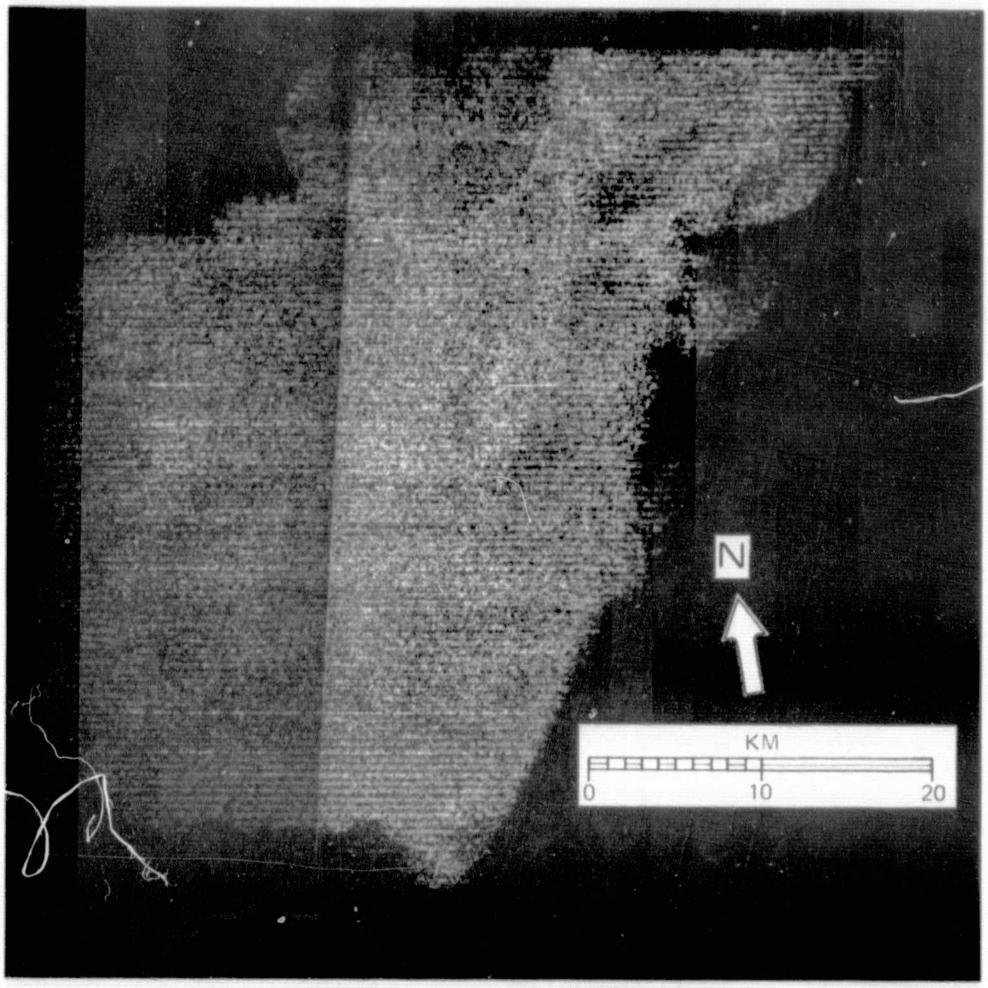
DISCUSSION

As reported previously (Ref 5), when the regression program was applied to the 3 June 1974 scene with the four LANDSAT bands as the independent variables, Band 6 alone was chosen by the regression procedure as providing the best correlation with most water quality parameters. Both Yarger (Ref 2) and Johnson (Ref 3) also found this to be true in Kansas reservoirs and in Chesapeake Bay, repectively. It was suggested (Ref 5) that the selection of Band 6, in the stepwise regression analysis, may have been caused by the noticeable atmospheric haze which causes non-uniform measurements of scene radiance and degrades the correlations in the two visible bands, Bands 4 and 5. When the four LANDSAT bands and the ratio of bands were applied as independent variables to the 3 June 1974 scene, a ratio of bands was chosen by the regression program as providing the best correlation with most water quality parameters. The fact that a ratio is a best choice for mapping water quality parameters was again verified by using bands and the ratios of bands in regression processing the 31 July 1975 scene, the results of which are observed in Table 2 and the figures of this paper. Table 2 shows that the ratio of Band 4 to Band 5 is sufficient to map the concentrations and distribution of chloride, conductivity, total Kjeldahl nitrogen, total phosphorus, and chlorophyll $\bar{a}$ with a correlation coefficient of 0.869 or more. Temperature and Secchi depth preferred Band 5 alone.

It should be emphasized that LANDSAT measures color or volume reflectance of the water and does not, for example, measure temperature, chloride, conductivity, etc. directly. Only a few water quality parameters; chlorophylls, algal populations, and particulate carbon; have a direct influence on the color or volume reflectivity of Saginaw Bay water. However, the other water quality parameters do correlate secondarily with color or volume reflectance to the extent that they all characterize the same water masses.

Figure 4 shows an image of the ratio of Band 4 to Band 5. The concentration and distribution of five water quality parameters can be interpreted directly from this image. The ratio values are indicated next to the appropriate breaks in the gray scale. The corresponding values for each of the water quality parameters have been calculated from either the equations shown in Table 2 or from plots of each variable, such as those shown in Figure 2. It should be emphasized that these values are accurate only within the ranges of standard error indicated in Table 2.

Analysis of the ratio image has confirmed some known features of circulation and water quality in Saginaw Bay. Previous surveys of the bay (Ref 7) have indicated that the predominant flow of Saginaw River water is northward along the eastern shore of the bay. Less turbid Lake Huron water dominates the outer bay and enters the inner bay chiefly along the the western shore. Zones of mixing and local circulation are apparent on the map, as are shoal areas where sediment evidently has been resuspended.



Saginaw Bay on 31 July 1975
Part of LANDSAT Scene 2190-15404

LANDSAT Band 4/5 Ratio	Gray Level	Chloride (mg/l)	Conductivity (micromhos)	Total Kjeldahl Nitrogen (mg/l)	Total Phosphorus (mg/l)	Chlorophyll $\bar{a}$ (μg/l)
1.32		23.8	300	0.939	0.038	53.1
1.36		21.6	290	0.832	0.033	45.5
1.40		19.3	279	0.725	0.029	37.9
1.48		14.7	258	0.512	0.020	22.8
1.56		10.1	237	0.299	0.011	7.6
1.64		5.6	216	0.086	0.002	-

Figure 4. Ratio Image and Predicted Water Quality of Saginaw Bay (Seven Gray Levels)

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A number of prominent water mass patterns can be identified from Figure 4. A lobe-shaped body of relatively clean Lake Huron water is located near the north edge of the ratio image. More turbid water enters the bay from the Saginaw River and flows counterclockwise along the shore. Also present are a few seemingly isolated areas of clean water within the bay. For example, note the area northwest of the most prominent point of land along the eastern shore.

The ratio image has been keyed to five of the 30 water quality parameters. The concentration and distribution of other water quality parameters may be obtained by their correlation with the five parameters mapped here. For example, sodium is highly correlated with conductivity and, if the relationship between sodium and conductivity is used, the conductivity map (ratio image) can also be transformed into a map showing the concentration of sodium over the bay. Similarly, the distribution of four major metals can be interpreted by their correlation with the chloride map.

The significance to water quality of each parameter measured in Saginaw Bay varies with the location and season. In general terms, however, the following applies to the July 1975 data. Temperature (also chemical and biological) gradients in the bay during the spring reflect the mixing of eutrophic Saginaw River water with oligotophic (and cooler) Lake Huron water. Thus, temperature may be used coincidentally to discriminate between waters of markedly different quality. Secchi depth estimates are used to approximate water transparency as affected by suspended particles and solutes. Chlorophyll $\bar{a}$ is also an approximate indicator of living algal biomasses. Conductivity, which varies directly with the concentration of dissolved ions, is generally high in eutrophic or polluted waters. Similarly, chloride is used here as a conservative tracer of enriched Saginaw River water.

CONCLUSIONS

LANDSAT digital data and ground truth measurements for Saginaw Bay (Lake Huron), Michigan, for 31 July 1975 can be correlated by stepwise linear regression and the resulting equations used to estimate "invisible" water quality parameters in nonsampled areas. The correlation of these parameters with one another indicates that the transport of Saginaw River water can now be traced by a number of water quality parameters, one or more of which are directly detected by LANDSAT. Chloride, conductivity, total Kjeldahl nitrogen, total phosphorus, and chlorophyll $\bar{a}$ are best correlated with the ratio of LANDSAT Band 4 to Band 5. Temperature and Secchi depth correlate best with Band 5.

Water quality parameters mapped from the linear regression equations will indicate which water quality parameter(s) is most reliable as a tracer to identify Saginaw River water as it circulates throughout the bay and is diluted by Lake Huron water. The resulting regression equations can be used to map the concentration and distribution of water quality parameters throughout the bay, given the appropriate LANDSAT measurements. These parameters need not be directly detectable by

LANDSAT, provided their concentration is correlated with some water characteristic that is detectable. The predicted values for each water quality parameter can be displayed on a TV monitor and color-coded and mapped onto film. Thus, LANDSAT monitoring, as an adjunct to conventional point-sampling, provides an economical basis for extrapolating water quality parameters from point samples to unsampled areas and provides a synoptic view of water mass boundaries that no amount of point sampling could provide.

REFERENCES

1. V. Klemas, M. Otlery, C. Wetle, and R. Rogers; "Monitoring Coastal Water Properties and Current Circulation with ERTS-1"; Third Earth Resources Technology Satellite-1 Symposium, 10-14 Dec 1973; Vol I, pp. 1387-1411.

2. H. L. Yarger, J. R. McCauley, G. W. James, L. M. Magnuson, and A. R. Marzoff; "Quantitative Water Quality with ERTS-1"; Third Earth Resources Technology Satellite-1 Symposium, 10-14 Dec 1973; Vol I, pp. 1637-1651.

3. R. W. Johnson; "Quantitative Sediment Mapping from Remotely Sensed Multispectral Data"; Fourth Annual Remote Sensing of Earth Resources Conference, Tullahoma, Tennessee, 24-26 March 1975.

4. R.H. Rogers, L.E. Reed, and V.E. Smith; "Computer Mapping of Turbidity and Circulation Patterns in Saginaw Bay, Michigan (Lake Huron) from ERTS Data"; Presented at ASP-ACSM Convention, 9-14 March 1975; NASA-CR-142923; NTIS Order Number E75-10321.

5. R.H. Rogers, N.J. Shah, J.B. McKeon, C. Wilson, L. Reed, V.E. Smith, and N.A. Thomas; "Application of LANDSAT to the Surveillance and Control of Eutrophication in Saginaw Bay"; Tenth International Symposium on Remote Sensing of Environment, 6-10 Oct 1975 (in press).

6. M.A. Efroymson; "Multiple Regression Analysis"; in A. Ralston and H.S. Wilf (eds.) Mathematical Methods for Digital Computers; John Wiley; pp. 191-203; 1960.

7. P.L. Freedman; "Saginaw Bay; An Evaluation of Existing and Historical Conditions"; EPA Report 905/9-74-003; April 1974.